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Design Study"

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(Statement A)

POWERSAIL HIGH POWER PROPULSION SYSTEM DESIGN STUDY

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ABSTRACT

In order to support the development of high power, thin film photovoltaic solar arrays by the Air Force Research Laboratory Space Vehicles Directorate, the Propulsion Directorate's Spacecraft Propulsion Branch carried out an in-house propulsion trade study and contracted for a propulsion design study with Virginia Tech University. The in-house study assumed a 100 kW array and performed the most in-depth analysis of the forces perturbing the array and of propulsion options to counteract these forces. Due to the 10 year duration of the mission, the recommendation was to reduce propellant mass by utilizing FEEP thrusters with their extremely high (8000 sec) specific impulse. However, due to the low level of maturity of FEEPs at the required power level, the trade study recommended a combination of the Busek BHT-200 Hall thruster and the AFRL μ PPT for a near-term mission. The Virginia Tech University design study looked at a 50 kW array and provided a more comprehensive look at the entire spacecraft system. They chose to employ pulsed plasma thrusters to meet their propulsion needs, thus minimizing complexity and integration issues rather than system mass

INTRODUCTION

The desire by the United States Air Force to maximize space utilization has led to a need for increased on-orbit electrical power. To enable this, the Air Force Research Laboratory Space Vehicles Directorate (AFRL/VS) is developing PowerSail: a two-phased program to demonstrate high power (100 kW to 1 MW) capability in space using a deployable, flexible solar array constructed of thin-film photovoltaics. Use of thin film photovoltaics in place of conventional solar arrays is projected to decrease mass and cost, while increasing packageability. The first phase will be a proof-of-concept demonstration at 50 kW, followed by an operational system at full power. The overall program has previously been presented¹ and will not be discussed in detail here. In support of this program, the AFRL Propulsion Directorate's Spacecraft Propulsion Branch (AFRL/PRSS) at Edwards AFB performed an in-house propulsion trade study in August 2000 to optimize the propulsion system based on the perturbing forces on the array.

In order to explore design issues in more depth, AFRL/PRSS commissioned a set of external design studies of propulsion systems intended to facilitate the operation of the PowerSail array. These studies were intended to perform mission and design trades to identify potential full-power applications of PowerSail

and the corresponding propulsion system requirements and design. A solicitation for the design studies was issued in October 2000, for a period of performance from 4 January to 4 June 2001. The final report from Virginia Tech University will be summarized, followed by general comments.

IN-HOUSE PROPULSION TRADE STUDY**Introduction**

PowerSail is a proposed spacecraft whose mission is to generate large amounts (50+kW) of electric power for delivery to a host spacecraft through a flexible umbilical. By offloading the power generation requirement to a separate spacecraft, many of the problems associated with large solar arrays, such as structural dynamics and deployment, can be minimized. PowerSail is envisioned to be a large thin-film solar array supported by four extendable booms, with a minimal bus to provide necessary support functions such as guidance, navigation, and control (GN&C); attitude determination and control; and propulsion.

PowerSail will require a dedicated propulsion and attitude control system to perform its mission. Even if the host spacecraft is not expected to maneuver, the

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large area-to-mass ratio of PowerSail will lead to differential orbital perturbations that will tend to drive the spacecraft into different orbits unless countered by propulsive force. Any maneuvers by the host spacecraft will also need to be matched by the PowerSail vehicle. Attitude control will be needed to maintain the PowerSail in a sun-pointing orientation.

PowerSail Parameters

The baseline design for the PowerSail spacecraft assumes a 100 kW delivered power requirement. This is satisfied with a 20m x 20m thin-film solar array with a central bus. The estimated total mass of the spacecraft is 210 kg, with 30 kg allocated to propulsion. A rough estimate of the mass distribution gives central moments of inertia $I_{xx} = I_{yy} = 6000 \text{ kg-m}^2$, $I_{zz} = 12,000 \text{ kg-m}^2$, with the +Z axis defined perpendicular to the array surface. The proposed structural geometry allows thrusters to be positioned on the central bus or at the corners of the vehicle. Due to the poor ballistic coefficient of the system, PowerSail is not envisioned for use at altitudes of less than 1000 km.

Propulsion Requirements

The dominant propulsion requirements on PowerSail, barring substantial maneuvers by the host spacecraft, will be to counter the effects of radiation pressure and atmospheric drag. PowerSail has a cross-sectional area of 400 m², a solar absorptivity of nearly 1.0, and will be oriented perpendicular to the sun at all times. This leads to a constant radiation pressure of 1.8 mN along the spacecraft -Z axis except during eclipse periods, and a total propulsive impulse of 57 kN-s per year.

Radiated IR and reflected sunlight from the Earth are also concerns in low orbits, though the intensity is lower and the geometry generally more favorable. Examining these effects over the range of expected orbital parameters gives maximum radiation pressures of 0.25 mN in the X and Y directions and 0.45 mN in the Z direction for a 1000 km orbit. Average values are 0.15 mN and 0.25 mN respectively, with a total impulse per year of 17 kN-s per year.

At 1000 km, atmospheric drag is negligible compared to solar radiation pressure except during periods of anomalously high solar activity. However, if ten-year mission lives are considered, the spacecraft must be designed to handle a worst-case solar max scenario. This is found to result in peak drag forces of 0.15 mN in the X and Y directions and 0.30 mN in the Z direction. Average values are less than 0.02 mN, and the expected propulsive impulse is only 1 kN-s per year.

In addition to translational thrust, the PowerSail propulsion system must be able to counter disturbance torques. The substantial moments of inertia of the PowerSail give rise to large gravity gradient torques, and the requirement that the solar array remain oriented towards the sun precludes allowing the spacecraft to come to rest in a gravity-stable orientation. Countering this torque requires a maximum of 8.8 mN-m of control authority with an average value of 4.4 mN-m and a total impulse requirement of 140 kN-m-s per year.

A small additional torque can arise if the host spacecraft casts a shadow onto the array, creating an imbalance in solar radiation pressure. Assuming a 20 m² spacecraft separated from the array by a 20 m umbilical results in a torque that requires a maximum of 2 mN-m of control authority to counter, with an average value of 0.15 mN-m and a total impulse requirement of 5 kN-m-s per year.

The combination of these propulsion demands leads to a requirement for up to 0.4 mN of thrust in the +X, -X, +Y, and -Y directions; 2.55 mN in the +Z direction; and an ACS torque authority about the X and Y axis of 8.8 mN-m. The required thrust impulse is 75 kN-s per year and the torque impulse 145 kN-m-s per year.

Propulsion System Options

The requirement to provide a constant propulsive force to offset radiation pressure will drive the propulsion system mass to excessive levels if conventional chemical rocket systems are used. The thirty kilograms of mass allotted to propulsion would not suffice for even one year of stationkeeping propellant with a conventional system. It will therefore be necessary to use advanced, electric propulsion systems for this application. Electric propulsion provides much higher specific impulse, and thus vastly reduced propellant consumption, in comparison to chemical rocketry. It can be handicapped by low peak thrust values and substantial power requirements, but those are not factors in this application - the peak thrust requirements are low, and abundant electric power is available.

Seven classes of electric propulsion system are considered in this application. Resistojets and arcjets electrically heat a propellant and thermally expand it to provide thrust. While the thrust mechanism is the same as used in chemical rockets, the specific energy imparted to the propellant is no longer limited by the energy density available from chemical reactions. Ion and Hall-effect thrusters electrostatically accelerate heavy ions to extremely high velocities to produce

thrust, by slightly different mechanisms. FEEP and colloid thrusters use electrostatic acceleration of charged liquid droplets, thus avoiding ionization losses associated with the Hall and ion thrusters. Finally, pulsed plasma thrusters use a capacitive discharge to ablate, ionize, and electromagnetically accelerate an inert solid propellant. While inefficient, the simplicity of a solid-propellant system with no moving parts is attractive for low-mass spacecraft applications.

Examples of all of these systems save the colloidal and FEEP systems are commercially available today and have flown on operational missions, and a flight-qualified FEEP system has flown on as an experiment on a space shuttle mission. Technical maturity should not be an issue for the use of any of these systems on a PowerSail demonstrator mission. Characteristics of suitable examples of each system are given in Table 1 below:

Thruster	Thrust	Isp	η
Surrey 100w Resistojet	100 mN	150s	55%
General Dynamics LPATS Arcjet	100 mN	500s	35%
Busek BHT-200 Hall Thruster	10 mN	1500s	45%
Hughes XIPS-13 Ion Engine	20 mN	2500s	50%
General Dynamics EO-1 PPT	1 mN	1000s	10%
AFRL micro-PPT	50 μ N	800s	5%
Stanford Lab Colloid	100 μ N	1500s	50%
Centrosazio 60W FEEP	1 mN	8000s	50%

Table 1: Thruster Options

In addition to the question of thruster type, thruster location also has to be considered. The spacecraft geometry lends itself to one primary thruster on the central bus providing +Z thrust, with four secondary thrusters on each corner boom for X/Y thrust and $\pm Z$ attitude control. The primary thruster would have to provide 2.55 mN of thrust and each secondary thruster 0.2 mN – with some of the thrusters described above, this would clearly require multiple thrusters per axis. This configuration is shown schematically in Figure 1.

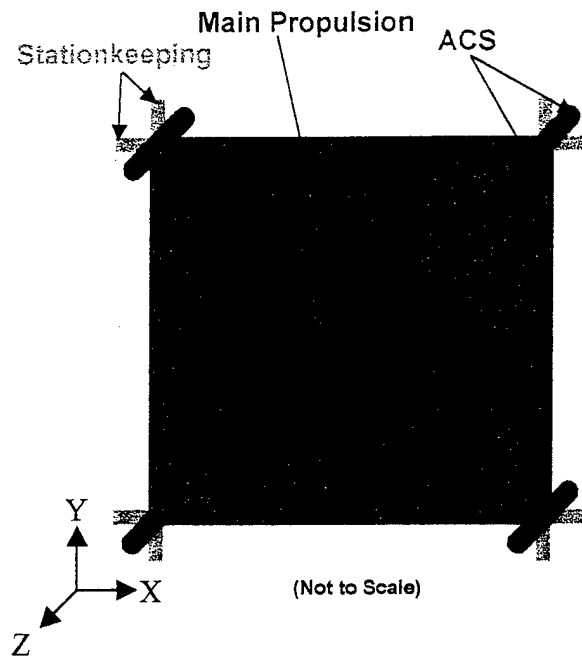


Figure 1: Thruster Configuration - Corner Mount

An alternate configuration would be to deploy a short boom, ten meters or less, from the central bus along the Z-axis. Again, a single primary thruster of 2.55 mN would be required, but only two clusters of four secondary thrusters would be needed. This would tend to reduce thruster mass and system complexity, and would eliminate the difficulty of mounting thruster systems at the corners of the deployable solar array. However, the reduction in moment arm for attitude control increases the thrust and propellant requirement for that mission. A 7 m boom (3.5 m moment arm) was selected – no study was conducted of the effects of the length of the boom on the propulsion masses. Additionally, this configuration has limited ability to counter a torque about the Z-axis, though analysis does not indicate that such a torque will be generated under normal operation. This configuration is shown in Figure 2.

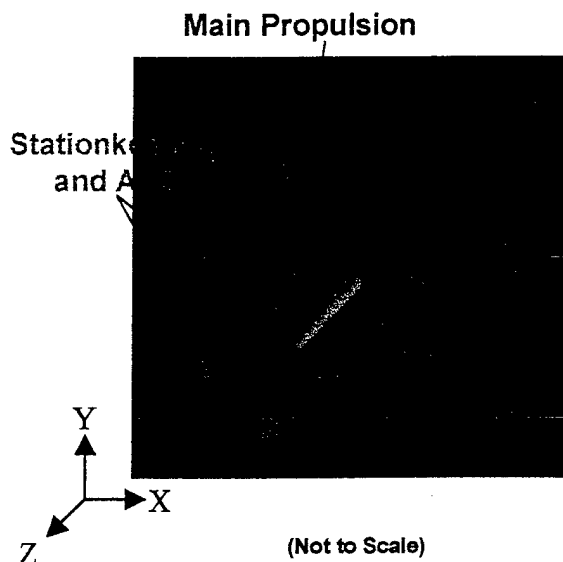


Figure 2: Thruster Configuration - Boom Mount

Propulsion Trade Analysis

Given the extremely tight mass budget set for the PowerSail spacecraft, any comparison of propulsion options must center on predictions of propulsion system mass. To address this issue, detailed mass estimates for propulsion systems using the various proposed technologies were constructed. A number of propulsion options were considered, with each of the potential primary propulsion systems examined for suitability as secondary propulsion as well, and with both center/corner and boom installations considered. Mass estimates for each system were broken down into five categories - thruster, power processing, propellant, propellant feed, and miscellaneous - with one or more line items in each category as appropriate. With central-boom installations, the mass of the boom itself was also charged against the propulsion system.

For each of the necessary items, commercial off-the-shelf hardware was specified whenever possible, preferably space-qualified but in the case of some power processing or propellant feed system components, ground or aviation hardware meeting relevant military specifications was used as a baseline. The intention is to reliably estimate the mass of a flight system rather than to actually design such a system. In some cases, commercial systems of different power levels were scaled linearly over a modest range to meet specific PowerSail requirements. For experimental thruster concept, flight-like laboratory test hardware was considered.

Separate evaluations were made for the requirements of 5- and 10-year missions, due to the different ΔV and propellant requirements. The total propulsion system mass requirements are given in Tables 2 and 3, below.

Primary Thruster	Secondary Thruster	5-Year Mission	
		Corner	Boom
Chemical Biprop	Chemical Biprop	241 kg	378 kg
LPATS Arcjet	LPATS Arcjet	178 kg	231 kg
XIPS-13 Ion	XIPS-13 Ion	160 kg	115 kg
EO-1 PPT	EO-1 PPT	92 kg	106 kg
EO-1 PPT	AFRL μ PPT	87 kg	141 kg
BHT-200 Hall	AFRL μ PPT	75 kg	129 kg
Centrosazio FEFP	Centrosazio FEFP	98 kg	66 kg
BHT-200 Hall	BHT-200 Hall	64 kg	84 kg
BHT-200 Hall	Colloidal Thruster	57 kg	92 kg

Table 2: Propulsion Mass Estimates - 5-Year Mission

Primary Thruster	Secondary Thruster	10-Year Mission	
		Corner	Boom
Chemical Biprop	Chemical Biprop	470 kg	746 kg
LPATS Arcjet	LPATS Arcjet	299 kg	430 kg
XIPS-13 Ion	XIPS-13 Ion	186 kg	157 kg
EO-1 PPT	EO-1 PPT	166 kg	229 kg
EO-1 PPT	AFRL μ PPT	161 kg	264 kg
BHT-200 Hall	AFRL μ PPT	145 kg	248 kg
Centrosazio FEFP	Centrosazio FEFP	105 kg	78 kg
BHT-200 Hall	BHT-200 Hall	107 kg	154 kg
BHT-200 Hall	Colloidal Thruster	104 kg	173 kg

Table 3: Propulsion Mass Estimates - 10-Year Mission

Conclusion

Because of the excessive propellant mass, it is clear that chemical propulsion is not appropriate for the PowerSail mission. On examination, the effective delta-V requirement for a ten-year mission is more than 4 km/s, which results in grossly excessive propellant mass. That being the case, the recommended option is the Centrosazio FEFP thruster. Their extremely high specific impulse dramatically reduces propellant mass.

However, at the power levels required for this mission, the technology is relatively immature and has a high dry mass. If a near-term demonstration is required, it may be more advantageous to utilize propulsion in a more advanced state of engineering development. In this case, we would recommend the use of a Busek BHT-200 Hall thruster on the central bus for primary propulsion, and four clusters of AFRL micro-PPT thrusters at the corners for lateral stationkeeping and attitude control. At 75 kilograms for a 5-year mission, this is nearly the lightest propulsion option found in the study, and is achievable with mature, near-term technologies. Both the BHT-200 and the AFRL μ PPT are scheduled to fly on the TechSat 21 demonstration mission in 2004. Furthermore, much of the potential integration difficulty associated with placing thrusters at the array corners is reduced by the compact, solid-state nature of the μ PPT systems.

VIRGINIA TECH UNIVERSITY²

The Virginia Tech University (VTU) design study covered all major spacecraft subsystems; including propulsion, structures, power, thermal control, communications, attitude determination and control (ADCS), command and data handling (C&DH), and umbilical. Only details relevant to the overall spacecraft design and the propulsion subsystem are presented here. It was performed under the auspices of the Aerospace and Ocean Engineering Department's Senior Design (Space) Course (AOE 4065).

System Synthesis

The objective of system synthesis is to conceptualize possible designs for PowerSail as well as to generate alternatives for components of each subsystem. Each of the alternatives generated in this section are compared using a value system design ranking. From these rankings top configurations are chosen to analyze further. This is a critical step in the design process, which helps identify alternatives while withholding judgment.

PowerSail Configurations

Four array configurations were considered: kite tail, sphere, fan, and flat array.

Kite Tail

The kite tail configuration (Figure 3) incorporates a formation of solar arrays to complete the mission objectives. Instead of a single large array, a group of smaller arrays provide a total of 50 kW of power. The arrays are strung in a line, each attached by a slack

umbilical. There are two types of satellites in this configuration: a command satellite and the power supply arrays. The command satellite is responsible for controlling the formation and attitude of the power supply arrays.

The command satellite is equipped with solar arrays and batteries for its own use. The array on the command satellite also provides some power to the host satellite. Each power satellite generates power for the host and itself. Batteries for the ADCS are located on each power satellite. The power needs of the host satellite determine the number of power satellites.

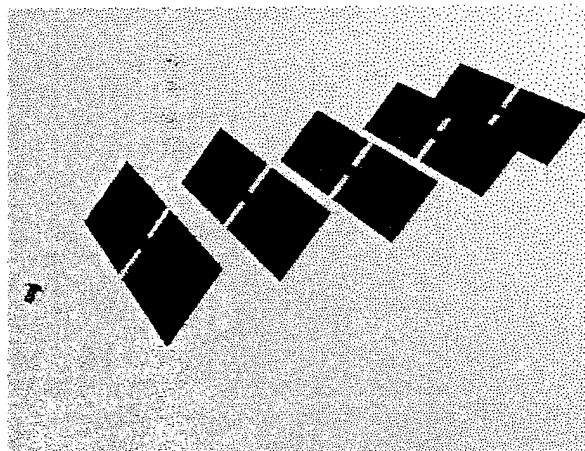


Figure 3: Kite Tail Configuration

Sphere

The sphere concept (Figure 4) is a single solar array. The array is a large sphere, akin to a balloon, covered with flexible solar cells. Filling the balloon with compressed gas inflates the array. The housing for internal components of the system is located at one edge of the array. The slack umbilical is attached to the housing. The thrusters for attitude control are located on the housing and on a mounting opposite the housing. There are supports located in and on the array to maintain the structure of the system. The pointing requirements of this system are decreased since the array is spherical and any orientation collects the same energy from the sun.

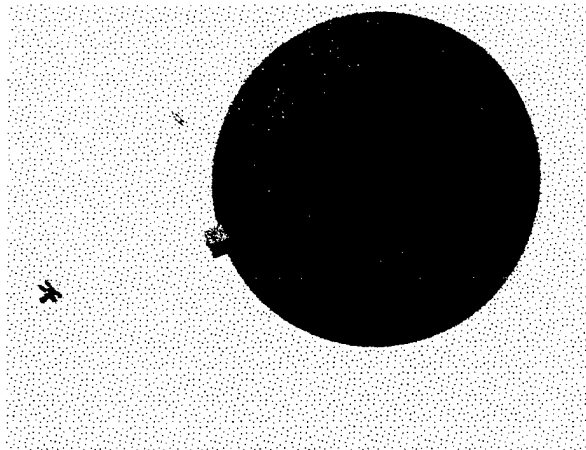


Figure 4: Sphere Configuration

Fan

Figure 5 shows the fan design, a structure that deploys in a similar fashion to a folding fan. When deploying, the solar array rotates about the central point creating a circular array. Similar to a Venetian blind, the solar cells will not likely be directly perpendicular to sunlight. The bus of the system is located in the center of the deployed structure. The umbilical is connected to the bus.

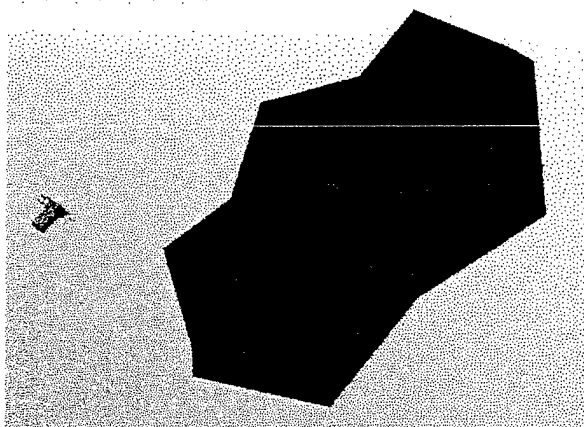


Figure 5: Fan Configuration

Flat Array

The flat array configuration is comprised of five deployable booms and a main bus. This configuration is a planar array with thin flexible solar arrays, in which the central boom deploys first. The side booms deploy simultaneously, deploying the flexible solar arrays. The bus structure is inherently small compared to the size of the array. The umbilical, thrusters, and attitude sensors are located on any part of this structure. This

configuration has a relatively small stowed volume and mass. The booms can also be designed to retract if needed.

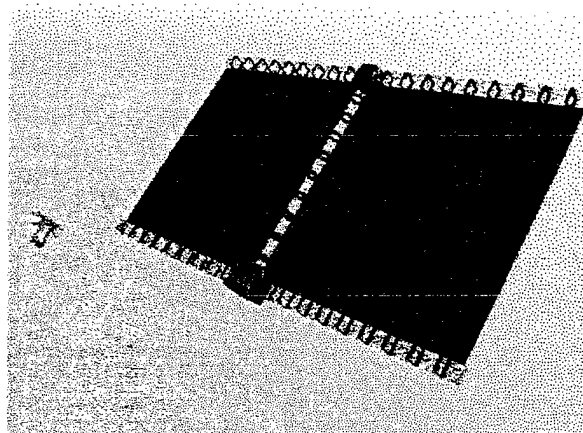


Figure 6: Flat Array Configuration

Propulsion Options Considered

The primary purpose of the PowerSail propulsion system is to maintain the proper position of the array in orbit relative to the host spacecraft. Forces such as solar radiation pressure and atmospheric drag must be countered. These maneuvers must be carried out so that the umbilical does not wrap around the array. The propulsion system must also counteract any dynamics that are induced in the array by the umbilical.

The long lifetime requirements projected for an operational system (10 years) results in a desire to reduce propulsion system propellant mass, making electric propulsion a highly attractive option. There are a growing number of space-rated and production electric propulsion systems. An electric propulsion system accelerates a working fluid to high velocity (in comparison to other propulsion types) to produce thrust. The high velocity, charged particle nature of electric propulsion plumes can present issues in multi-satellite formations. Several types of electric propulsion systems were considered for use in the PowerSail project: resistojets, arcjets, ion engines, Hall thrusters, and pulsed plasma thrusters. The resistojet and arcjet have lower specific impulse than the other systems, leading to higher propellant masses. However, they have neutral plumes, which may be advantageous given the close formation of the array and host. Hall thrusters and ion engines have the highest specific impulses, and thus the lowest propellant masses. However, their large dry masses are a concern and their ionized plumes may cause spacecraft interaction issues. Pulsed plasma thrusters (PPTs) are inefficient, but are simple, reliable,

and use a solid propellant (Teflon); which makes them attractive for positioning at the end of a deployable structure since it avoids the need to run propellant lines from a centralized tank or, alternatively, carry separate tanks for each thruster location.

System Analysis

The impact of the array configuration on the propulsion subsystem was analyzed. This information was combined with the impact on other subsystems to select a final design.

Kite Tail

This configuration creates a number of different problems for the propulsion system. Each satellite in the kite tail has its own propulsion system and attitude thrusters, so the mass of the overall system is larger than a centralized configuration. Although each satellite needs a smaller thruster size and propellant mass, the number of thrusters and overall mass of propellant for all satellites offset this advantage.

Since a slack umbilical connects each satellite, wave propagation down each umbilical creates a need for thruster operation. This additional need for thruster operation increases the amount of propellant required as opposed to other configurations. It is assumed that the umbilical between each satellite is long enough that the plume from the thrusters will not interfere with the other satellites in the chain.

The system needs small controlled bursts to maintain the attitude of the kite tail. The best system for this is a Pulsed Plasma Thruster (PPT). Ion engines and Hall thrusters create more thrust than is necessary and are too massive for use on the smaller satellites. Arcjets and resistojets also are more massive than the PPTs, and have greater propellant mass. The sizing of the PPTs is dependent on the location of the thrusters and size of each satellite. It will be difficult to integrate the thrusters into the array because of the minimal support structure.

Sphere

The sphere configuration for PowerSail reduces the need for propulsion system operation to maintain attitude control since the spherical array always has an equal amount of surface area facing the sun. The reduced pointing requirements lead to a decrease in thruster operation. However, because the array is spherical, it will experience cosine losses in areas not perpendicular to the sun vector. Due to these losses, the sphere configuration is the largest of the options

considered, thereby increasing both the solar radiation pressure and drag force that the array experiences. The result is an increase in primary propulsion requirements, overwhelming the savings from pointing.

This configuration does not have the stringent impulse bit requirements of the kite tail. It optimizes well for a small Hall thruster or ion engine. A large PPT could also be used, but would suffer from high dry mass and low efficiency. The system would, however, benefit from the simplicity of the PPT. Again, there are expected to be integration issues.

Fan

The fan configuration is akin to a single piece of the kite configuration, although it is much larger than a single piece of the kite tail. Overall, the array area is equivalent, but the mass will be less since it is centralized. Thus, the drag and solar radiation pressure will be comparable to the kite tail and less than the sphere. The pointing requirements are less than the kite tail since there is only one array to point, but more than the sphere which requires virtually no pointing.

This fan does not have as stringent of an impulse bit requirements as does the kite tail, but the small impulse bit of the PPT is still very compatible. A small ion engine or Hall thruster are options for the fan because it has a larger mass than the individual kite tail sections.

Flat Array

The flat array configuration is a planar array with booms to support the array. It is similar in area and pointing requirements to the fan. The additional mass of the support booms will increase the propulsion needs of the system. However, the additional stiffness that the booms supply will decrease dynamic interaction within the array from the umbilical or other perturbing forces, thereby partially offsetting the increase due to boom mass. The primary advantage of the flat array from a propulsion standpoint is integration. The booms provide ample thruster mounting locations, making integration much simpler than for the other configurations.

Due to the similar propulsion requirements, the same propulsion options that benefited the fan also work well for the flat array: PPTs, small ion engines, or small Hall thrusters.

System Analysis Conclusions

An objective hierarchy and a value system design were applied qualitatively based on the results of the system

analysis. From an overall system perspective, the two most attractive options were the sphere and the flat array. The primary advantages of the sphere were its lack of pointing requirements (which leads to both decreased propulsion mass and operational cost) and ease of deployment. Its disadvantages were that the larger array drove up the mass and volume of the array, thus increasing the impact on the launch vehicle. The three other configurations (kite tail, fan, and flat array) have similar propulsion requirements. The advantages of the flat array were low mass and stowed volume, a reasonable deployment system, and, most importantly, ease of integration of components such as the bus and propulsion system. The disadvantages are its pointing requirement and dynamic interaction issues. Based on these considerations, the flat array appeared to be the most advantageous and was selected for the system.

The resultant array must provide 50 kW to the host in addition to powering its own propulsion system, ADCS, computer, and battery. These components will consume an additional 2.6 kW of power. The array is composed of Copper Indium Diselenide (CIS) thin film photovoltaic solar cells³. These cells operate at an estimated efficiency of 17%, provide an energy density of 125 W/m², and a specific power of 200 W/kg. The final configuration of PowerSail is an array split into 14 panels to allow for deployment via rigidizable, inflatable booms. Each panel is 3m x 10m for a total area of 420 m². PowerSail's mass, including propulsion, solar array, umbilical and structure is approximately 800 kg.

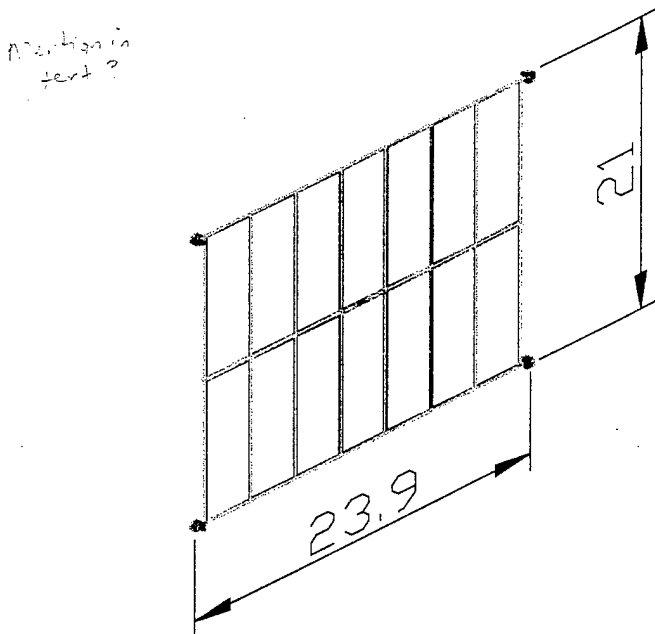


Figure 7: PowerSail Array Dimensions

The overall system, separated by major subsystem, is shown schematically in Figure 8.

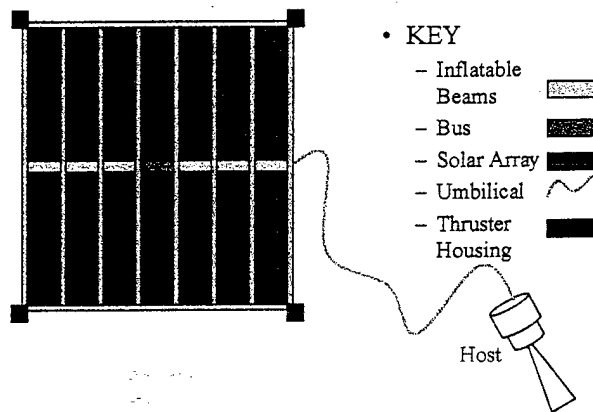


Figure 8: PowerSail System Schematic

Propulsion System Optimization

The propulsion subsystem of PowerSail has two main requirements. The first is maintenance of the formation between PowerSail and the host. The system must be able to maintain the leader-follower formation with the host satellite, while having low mass and power requirements. The umbilical that attaches the two satellites is a fixed length and the distance between the two can't exceed this length. The second requirement of the propulsion system is to keep PowerSail sun pointing as much as possible. In the targeted orbits, above 1000 km, the dominant force acting on the PowerSail array during its orbit is solar radiation pressure.

System Modeling

The effects of solar radiation pressure on the PowerSail orbit are computed based on algorithms that determine whether or not the array is within sight of the sun. If it is, the code applies forces from the solar radiation pressure to alter PowerSail's orbit. The net result is an increase to the eccentricity of PowerSail's orbit.

The host provides its own stationkeeping and orbit maintenance. The data obtained from modeling the leader-follower formation of the host and PowerSail around the earth show that the distance between the host and PowerSail exceeds the umbilical length by several kilometers in less than one orbit when not using a control system. The magnitude of the separation between the host and PowerSail is shown in Figure 9, and a planar view is shown in Figure 10. To counter this separation, the propulsion system acts to correct the orbit of the PowerSail. A total of 84.9 kN-sec per year

of solar radiation pressure must be counteracted to maintain the desired leader-follower formation. Therefore, over the ten year lifetime, a total of 849 kN-sec must be provided by the propulsion system to counteract solar radiation pressure.

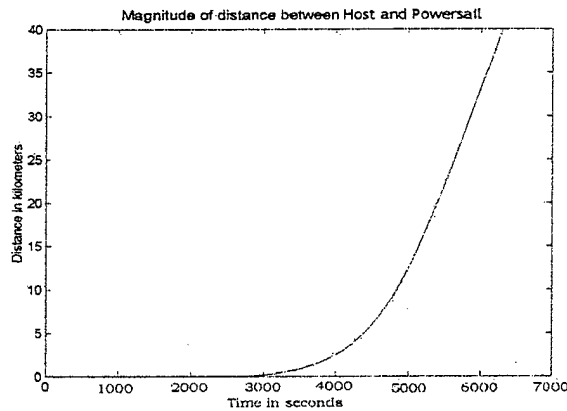


Figure 9: Magnitude of the Distance Between the Host and PowerSail vs. Time With an Inactive Control System

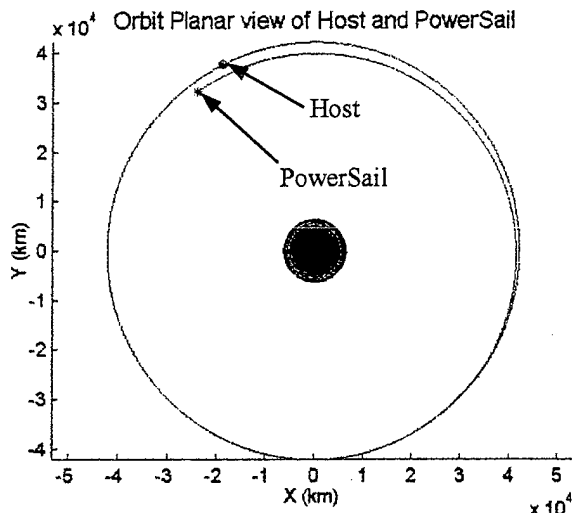


Figure 10: Orbit Planar View of the Host and PowerSail in a Geostationary Orbit after One Orbit With an Inactive Control System

Propulsion Subsystem Definition

PowerSail uses clusters of Pulsed Plasma Thrusters (PPTs) placed in corner modules. The data obtained from the orbit model gave the total impulse needed per year to maintain the formation. The propulsion system has a total of 40 thrusters located in four separate corner modules. An example of a module is shown in Figure 11. The overall dimensions of the module are 0.5 m by

0.5 m. The four thrusters oriented in the +Z direction are primarily intended to counter the solar radiation pressure. The thruster pairs pointed along the other axes are intended to counter other torques and provide ACS for the PowerSail. The PPTs chosen for this analysis are manufactured by General Dynamics, who provided information on their operation and mass estimates.⁴

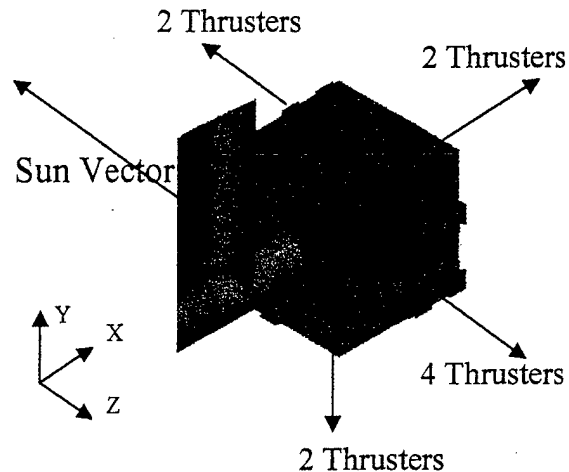


Figure 11: Propulsion Module

PPTs were chosen for a number of reasons. They use solid propellant, which eliminates the need for a propellant feed system and avoids the possibility of sloshing a liquid propellant, which could increase the vibration of a thruster module during operation. They have low dry mass and are durable, scaleable, and highly adaptable. They can deliver a precise impulse bit, which could enable them to perform array vibration damping.

PPTs have adaptable power supply systems. The power supply scheme for a cluster of PPTs can include up to four thrusters per capacitor and up to four capacitors per Power Processing Unit (PPU). Thus with a cluster of thrusters in a single small thruster module, the power system can control the whole module while keeping mass at a minimum. The power supply configuration for the PPTs in each module consists of 3 capacitors and 1 PPU for all 10 thrusters. This integration lowers system mass considerably, since capacitors have the largest amount of dry mass. The thrusters also have extra Discharge Initiation (DI) circuits to increase life. The total impulse capability of a PPT is not based on amount of propellant for the thruster; the limiting factor is the spark plug and DI circuit. Currently, General Dynamics spark plugs and DI circuits are rated at approximately 10 million pulses, corresponding to 0.65 kg of Teflon propellant and 8.6 kN-sec of total impulse. It is possible to use up to four sets of spark

plugs and DI circuits on a single thruster in order to increase its overall total impulse. With four DI circuits, the propellant available to a single thruster is increased to 2.6 kg and the total impulse is increased to 34.4 kN-sec. The four thruster groups pointed in the +Z direction for solar radiation pressure counteraction have four DI circuits per cluster, while the thruster pairs pointed in the other directions - which have lower total impulse requirements - have two DI circuits per thruster.

PPTs also have a scaleable firing rate. They fire in pulses, at 100 J per pulse. As long as power is available, the thrusters can fire from 1 Hz to 20 Hz. There is no ramp up in pulse cycling either. Thus, the amount of impulse provided is variable up to a maximum amount. The specific impulse of General Dynamics pulsed plasma thrusters is roughly 1350 seconds. The PowerSail thrusters fire at a nominal rate of 2 Hz; however, this can be increased if an abnormally large or small separation occurs between the host and PowerSail. The maximum amount of power available in normal operations for the firing of the PPTs is set for 4 thrusters firing in 3 axes at 2 Hz. This worst-case scenario requires 2.4 kW.

Each pulse provides 860 μ N-sec impulse. With such a low impulse bit, the thrusters can be used as an active damping system to reduce the structural vibrations of PowerSail. However, operating the thrusters in this manner would increase the propellant mass that the PPTs must carry and consume.

The dimensions of a thruster pair are shown in Figure 12 and a photo of the thrusters is shown in Figure 13. A schematic of a generic pulsed plasma thruster is Figure 14. The mass breakdown of specific components and total system mass is in Table 4.

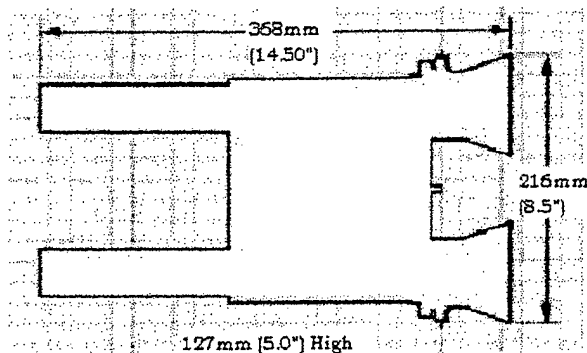


Figure 12: Dimensions of a PPT Pair

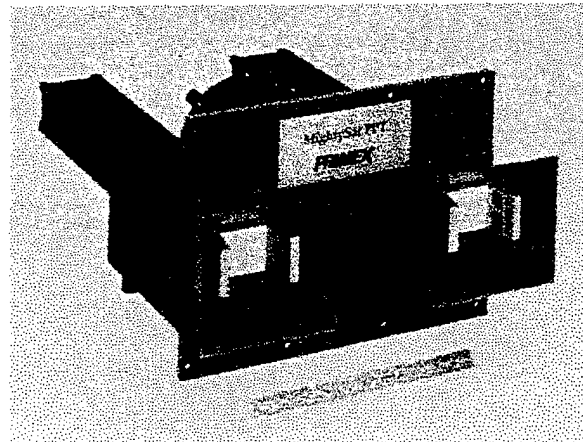


Figure 13: Photo of a General Dynamics PPT Pair Developed for the AFRL MightySat Program⁵

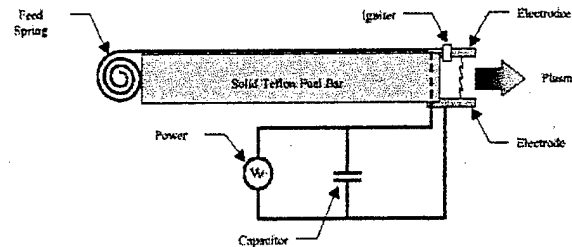


Figure 14: Schematic of a Generic Pulsed Plasma Thruster

Component	Mass (kg)
Thruster + Housing	0.54
Capacitors	2.32
PPU	0.52
DI Circuit	0.2
Overall System	
Thrusters & Propellant (40)	127
Capacitors (12)	27.8
PPUs (4)	2.2
Total System Mass	157

Table 4: PPT Mass Properties

Summary

PowerSail needs to provide 50 kW of power to a host spacecraft ranging in orbit from 1000 km to geostationary. It has a lifetime of 10 years which leads to the need to use electric propulsion to maintain the formation between it and the host. The power is transmitted to the host using a slack umbilical.

The final configuration of PowerSail is a flat array split into 14 panels. Each panel is 3m x 10m for a total area of 420 m². PowerSail's mass, including propulsion, solar array, umbilical and structure is approximately 800 kg. This is a fairly low mass considering the size of the solar array when deployed.

The dominant propulsion driver is the need to counteract 84.9 kN-sec of solar radiation pressure per year over the 10-year lifetime of the system. The propulsion system chosen is the PPT manufactured by General Dynamics. PPTs are a good choice as a propulsion system for a number of reasons including solid propellant, adaptable power systems, and low dry mass. These thrusters will maintain the formation between PowerSail and the host. They also keep PowerSail pointing toward the sun. There are a total of 40 PPTs, clustered into four thruster modules. The maximum available power allotted for the PPTs is 2.4 kW.

COMMENTS AND CONCLUSIONS

AFRL was pleased with the results of these design studies. The two studies used different approaches, had different criteria, and thus obtained different results.

The in-house propulsion trade study performed a more in-depth analysis of the forces perturbing the array and of propulsion options to counteract these forces. Due to the long duration of the mission, the recommendation was to reduce propellant mass by utilizing FEEP thrusters with their extremely high (8000 sec) specific impulse. However, due to the low level of maturity of FEEPs at the required power level, the trade study recommended a combination of the Busek BHT-200 Hall thruster and the AFRL μ PPT for a near-term mission.

The Virginia Tech University design study provided a more comprehensive look at the entire spacecraft system, and thus did not go into the same depth for the propulsion subsystem. In choosing to employ pulsed plasma thrusters to meet their propulsion needs, they chose to minimize complexity and integration issues rather than simply minimizing system mass.

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